A NEW APPROACH TO MODELLING VEHICLE INTERACTIONS WITH ROADSIDE RESTRAINT SYSTEMS

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ABSTRACT

Vehicle interactions with roadside restraints such as crash barriers and bridge parapets are extremely complex events and the outcome can be greatly influenced by very local effects. Such impacts typically take place over a time period of 2-3 seconds which presents particular challenges when simulating the process numerically. The inclusion of these local effects necessitates very small time increments during the analysis and this consequently results in extremely long analysis times.

A technique has been developed that predicts the outcome of vehicle to roadside restraints in a computationally efficient manner. The methodology capitalises on advanced features and material models available in the LS-DYNA finite element code, and avoids the use of detailed vehicle models that can over-complicate the analysis and lead to vehicle-specific performance predictions for the barrier. The technique uses advanced beam element and contact formulations and makes use of a generic vehicle representation. Use of a generic vehicle in this form removes the possibility of vehicle-specific performance predictions for the barrier, and allows the computational resources to be focussed on analysis of the barrier rather than the vehicle, which is effectively only a loading mechanism for the barrier.

The approach has been validated throughout against test results and has been proved capable of predicting all conventional roadside restraint performance measures including injury measures as defined in BS EN 1317. Validation has taken place against a range of restraint systems including aluminium parapets, reinforced concrete parapets and wire-rope safety fences, which makes the approach an effective tool for establishing legislative test conditions and for researching and predicting RRS performance.

INTRODUCTION

Roadside restraint systems are to be seen on highways across the world. They are systems designed to control the trajectory of errant vehicles leaving the carriageway and can serve a number of purposes depending on the reason for their installation. Safety fences are usually installed over long lengths of carriageway either on the central reserve or along the verges, and are intended to contain and redirect a vehicle. Parapets, however, are usually installed in locations where there is a sudden drop alongside the carriageway, the most common location being on a bridge deck. For economic reasons the width of a bridge deck is limited and this requires parapets to deflect less during an impact than safety fences, although there are different performance requirements for each depending on the installation and intended use.

The regulations covering roadside restraints are currently under review, and as a result the existing UK documents such as BS6779 are being superseded, or will incorporate, EN (Euronorm) 1317 as it develops. EN1317 defines different classes of roadside restraint system according to the speed and mass of the vehicle that they are intended to contain and the performance of the systems under the impact. Vehicles covered by the standard range from 900kg passenger vehicles through to 30 tonne tankers. In order to be qualified to either BS6779 or EN1317, full-scale impact tests are necessary between a vehicle and a representative length of the roadside restraint. These tests are expensive and hence it is desirable for manufacturers of these systems to predict the outcome and to thereby minimise the risk of failure involved.

Systems of the type under consideration in this paper are frequently installed over long stretches of road, and hence they are designed to use the minimum amount of material while remaining compliant with the standards. Also, compliance with the standards requires balancing a structure stiff enough to restrict the deformation of the system while remaining flexible enough so as not to generate unnecessarily severe loading on the vehicle occupant. For these reasons an accurate predictive technique is required by manufacturers that is cost effective and yet can provide sufficient detail to influence the design of the system.

A number of approaches are in use by different organisations around the world in order to predict the interaction of vehicles with roadside restraint systems. TRL Limited has developed a methodology that has been demonstrated to reliably predict the outcome of these interactions without incurring a disproportionately high computational overhead. The particular difficulties that this application presents to the mathematical modeller are discussed in this paper along with the solution developed by TRL Limited.

DYNAMICS OF A ROADSIDE RESTRAINT SYSTEM IMPACT

An impact between a vehicle and a roadside restraint system is an extremely complex event with many hundreds of individual collisions, interactions and contacts taking place. The event usually takes place at high speed (test speeds are up to 110kph) meaning that the materials involved are strained at very high rates. The event is also very violent as a result of the high energy involved, resulting in catastrophic failure of materials and components and redirection of the vehicle which can sometimes become completely airborne.

The initial contact (typically at an impact angle of 20°) generally occurs between the superficial exterior bodywork of the vehicle and the roadside restraint. Progressively more of the vehicle structure becomes involved in the contact as the vehicle bodywork deforms and, depending on the stiffness and design of the roadside restraint, the restraint itself deforms and/or fractures.

After these initial interactions, a number of further potential interactions may take place. Examples of these phenomena include:

- Wheel climb up the barrier as a result of the wheel rotation
- Wheel snagging on components of the restraint system
- Suspension and steering damage which may subsequently modify the trajectory of the vehicle
- Snagging of vehicle body panels on the roadside restraint system components
- Transmission damage
- Major structural failure of vehicle parts

Most of these events are somewhat chaotic in nature and as a result are very difficult to predict reliably, indeed they may not even occur on two successive, nominally identical, tests. However, the occurrence of one of these interactions may completely change the outcome of the test.

In carrying out a test to one of the relevant standards, certain criteria are recorded and compared against predefined criteria. The tests themselves are usually carried out at speeds between 40 and 70 mph, and at an impact angle of 20°, although some tests can be defined at higher impact angles in order to investigate ‘pocketing’ of the vehicle, in which case the vehicle embeds itself in the roadside restraint and comes to an abrupt halt rather than being deflected by it. Criteria to be recorded and assessed include:

- the restraint dynamic deflection (i.e. the greatest deflection of the system at any time during the impact)
- positioning of the vehicle relative to the restraint (usually expressed as ‘wheel penetration’, or the extent to which the leading vehicle wheel crosses the line of the restraint system)
- vehicle trajectory subsequent to the impact (an ‘exit’ box is usually defined through which the vehicle should pass)
- severity measures, of which 3 are conventionally used based on vehicle accelerometer readings (note that crash dummies are not generally used in these tests).

DIFFICULTIES PRESENTED TO THE NUMERICAL MODELLER

The most difficult aspect of modelling vehicle impacts with roadside restraint systems is the calculation of a solution within an acceptable elapsed time. There are a number of factors which all work against this objective.

- Timescale of actual event
  The timescale for impacts of this type can be in the order of seconds, whereas most crash simulations represent a timescale measured in 10s of milliseconds. Modelling to the same level of detail as a conventional crash simulation could therefore potentially take 100s of times longer to process, which is unacceptable given that conventional crash simulations can take in the order of days to process even on multi-processor platforms.
- Detailed behaviour important
  The performance of a roadside restraint system is very dependant on the behaviour of the system at a detailed local level, for instance material fracture at the base of posts, local buckling of the rail component and failure or deformation of the post to rail connection. In order to capture this local behaviour, a detailed model of the relevant components is required and this implies small elements, a small timestep and therefore a long analysis time. The conventional test length for such systems is approximately 30m, hence any detailed modelling must be considered in the context of its implementation over a very large structure.
- Capture of local interactions
  In a similar manner, the performance of the system can be greatly dependant on local interactions between the vehicle and the restraint system, such as snagging of body panels or wheels. In order to capture these local events, a very detailed model is again

required with the associated implications for timestep length and analysis time.

- High energy, high speed event
  The whole event is a very high speed, high energy and highly non-linear event. This combination of factors tends to drive the timestep down to a very small value which again increases the analysis time.

- In addition to the timescale issues discussed above, a number of other phenomena need to be represented in the model in order to represent the event fully.

- Friction is an important parameter in these impacts and occurs at a number of locations. The most important frictional contacts are between the vehicle and the rails of the roadside restraint system (as it slides along the barrier) and between the vehicle and the road surface. A reasonable estimate of the vehicle to restraint system friction can be made, but this can be variable depending on the extent of damage to the vehicle which may cause scoring of the barrier, thereby increasing the friction. Interaction between the vehicle and the road must be representative of a rolling vehicle up to and until it contacts the barrier. During interaction with the barrier, some or all of the wheels may leave the ground thereby removing any frictional influence, or damage may occur to one of the wheels and thereby increase friction. The steering may also become damaged modifying the trajectory of the vehicle.
- An important phenomenon that occurs in these impacts is ‘connection’ between the restraint system and the vehicle. As the vehicle deforms, the rails of the restraint system can form a groove in the vehicle bodywork that locates the vehicle relative to the restraint system. This effect can be very important for the effective redirection of the vehicle and is often employed deliberately. The model must therefore be sufficiently detailed to allow this effect to occur in a representative manner.

A conflict faced in the whole process of modelling these events is that the roadside restraint system is the focus of the analysis, with the vehicle acting largely as a loading mechanism, the detailed response of which is not of interest in itself apart from any implications for the barrier. It would therefore be easy in these analyses to expend the majority of the computational effort on the vehicle, rather than the restraint system which is usually a simple engineering structure requiring straightforward representation. However this balance of effort between the two interacting components does not reflect the relative level of interest in each.

As a result of all these issues, careful consideration must be given at the outset of the modelling process as to what the intended use of the model will be. Such models may be used as research devices to understand the generic behaviour of different types of roadside restraint, and the optimum manner in which to employ each, or as design tools with which to predict the outcome of a qualification test and hence reduce the risk of test failure. The application of the model will define the parameters and phenomena that require specific representation and capture in the model. By implication, this will also imply which phenomena will require representation, approximation or justifiable omission.

DETAILED VERSUS GENERIC VEHICLE MODELS

The conventional approach to modelling of roadside restraint system impacts is through use of detailed vehicle models developed for crash analysis applications. These models are available from manufacturers if an agreement can be reached over their use, or alternatively some models are available on the internet, although the quality of such models is often highly questionable. If suitable detailed vehicle models can be found, then there are implications for their use that should be considered.

- The majority of computing effort is directed at the vehicle rather than the barrier.
  This issue was discussed in Section 0, but the use of detailed crash models that comprise 10s of thousands of elements highlights this particular issue. Crash models are developed for the specific application of ‘head-on’ impacts into rigid or deformable barriers, and are not well suited to shallow oblique impacts into a highly deformable structure. While the models will solve and provide a solution, the benefit of the additional detail is not necessarily commensurate with the additional computational cost, and the increase in analysis time can be considerable.
- The results of the simulations can be specific to the vehicle model chosen.
  A danger of using a detailed model of a specific vehicle is that the results may be unique to that particular vehicle. Given that the restraint system performance can be very dependant on very localised interaction effects with the vehicle, use of a specific vehicle model may result in an outcome that is not representative of the wider vehicle fleet. A specific vehicle result may be of interest when modelling a specific test condition where the

exact vehicle type is known, but if this is the case then the following point should also be considered.

- The detailed response of the vehicle cannot easily be validated.
  Many of the local interactions between a vehicle and a roadside restraint system are somewhat chaotic in nature and may not occur in the same way, or indeed at all, on two successive tests. However, the deterministic nature of numerical analysis is that the same result will occur every time. Any detailed phenomena predicted to occur by the simulation are therefore difficult to validate as they may not be seen during a test despite being a plausible outcome.
- Very long analysis times.
  As a result of all these issues, very long analysis times can result and the benefits of using detailed vehicle models must be balanced against the penalties and uncertainties associated with their use.

A potential solution to many of the difficulties and conflicts discussed above and in Section 0 is the use of a much simplified representation of the vehicle, i.e. a 'generic' vehicle model. However, a generic vehicle approach must be handled carefully as the vehicle model has a number of vital functions to fulfil:

- The vehicle must absorb the correct proportion of the impact energy and in a representative manner so as to impart a representative loading into the roadside restraint and to be redirected from the barrier with the correct trajectory
- The vehicle should deform in such as way that it allows 'connection' with the roadside restraint
- The vehicle should have the correct mass and inertia properties for the class of vehicle that it represents
- The vehicle should interact with the road in a representative manner.

A generic vehicle model will, by definition, not specifically include some of detail necessary to capture all potential interaction phenomena. However, through use of advanced features and material models available in state-of-the-art finite element codes, a representation of the vehicle has been developed by TRL Limited that interacts with roadside restraint systems in a manner typical of a given class of vehicle. Examples of two such generic vehicles are given in Figures 1 & 2.

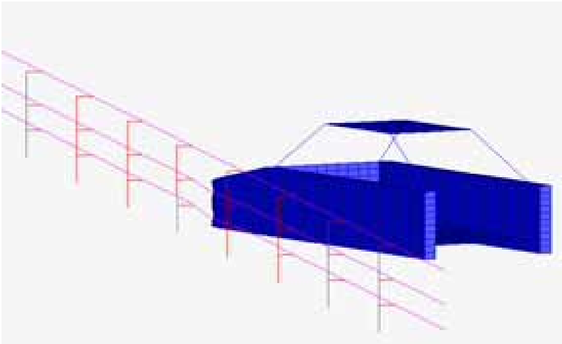

Figure 1: Generic model of a car

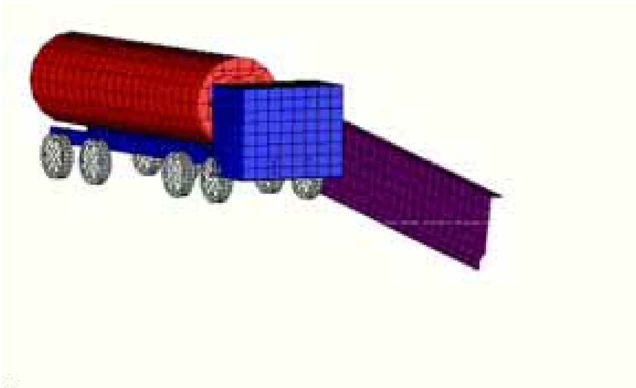

Figure 2: Generic model of a 30t tanker

The generic vehicle model validates well against test data from a number of different types of roadside restraint system and these are described in Section 0. Although some phenomena will not be captured by the generic model in its current state of development due to the simplifying assumptions made, features can added in a cost effective manner according to the demands of a given application. Such developments may include specific modelling of the wheels in order to provide a more accurate prediction of wheel penetration and prediction of 'wheel snagging' on the roadside restraint system.

An additional benefit of this approach is that the addition of detailed features can be implemented in such a way as to enable sensitivity studies on those features. For instance, wheels may be added in such a manner that their location on the vehicle could be varied easily. A sensitivity study would then provide insight into the mechanism of wheel snagging and would allow countermeasures to be developed. Altering the wheel position or other feature on a detailed vehicle model would be a time consuming and complex remodelling exercise.

In conclusion, while detailed vehicle models are known to be effective and are in widespread use (especially in the USA), they do have potential drawbacks which can be addressed through use of generic vehicle models. The remainder of this paper describes the application of generic vehicle models in impacts with various roadside restraint system types.

MODELLING OF THE ROADSIDE RESTRAINT

Methodology

As discussed in Section 0, the performance of road restraint systems is dependent on local design details such as the connection between the rails and the posts. A good representation of detail design features such as these would require as a minimum, a shell element model in order to predict the failure or deformation characteristics of the system. However, modelling to this level of detail is not feasible given that a length of at least 30m of the roadside restraint system is usually required for a full scale test.

An alternative approach has been developed at TRL which, in a similar manner to the vehicle representation, uses advanced features of finite element codes to represent the restraint system in a simplified manner. However, unlike the vehicle representation, a generic approach is unacceptable as it is the performance of a specific system that is desired from the analysis. As a consequence, any simplifying techniques employed must still represent the specific system design under consideration and its performance characteristics.

An example of the approach developed at TRL considers a bridge parapet in a 2-stage process involving a number of component models. As a first stage, detailed shell element models are developed of the key components of the restraint system, the key components possibly differing depending on the specifics of the system in question. These detailed models represent the restraint system components as closely as possible, and are capable of accurately predicting the performance of those components, including its failure modes. It is likely that these components would include as a minimum a single post model and an isolated rail model.

Once the detailed models have been developed, they are loaded using the generic vehicle model in a fashion representative of the loading they would see in a full impact analysis. Under these conditions the failure modes and performance of each component can be studied and compared against component test data if such data are available.

Having developed detailed models of each component, simplified representations using beam elements can be developed and correlated against the detailed models. A key aspect of this procedure is the selection of relevant criteria with which to compare the two models - these criteria should be accurate indicators of the component's function in the full system. It is at this stage that advanced features of the finite element code can again be used in the development of the simplified representations.

Once all of the simplified component models have been developed, they can be assembled into a complete representation of the roadside restraint system and analysed in combination with the generic vehicle model to predict the performance of the overall system in a robust and computationally efficient manner. Examples of the application and validation of this process are provided in the following sections in relation to different types of roadside restraint systems.

It has been found that while analysis of RRS impacts may take days to complete using detailed models of both the vehicle and the RRS itself, even with high powered hardware platforms, the use of the methodology outlined above combined with generic vehicle models can allow the analysis of a system in a matter of hours (typically 8 –10 hours). This saving in elapsed time and computing overhead can generate substantial benefits when modelling is used as a design tool and greatly reduce the time taken to produce research results.

Aluminium Bridge Parapet

Bridge parapets are essentially stiff structures intended to prevent a vehicle from leaving the carriageway and falling off the bridge deck. In the course of this action, the bridge deck itself should not be damaged as this would entail a very lengthy and costly closure and repair of the bridge itself, and hence the loads transmitted into the bridge deck must be limited.

Bridge parapets fabricated from aluminium achieve these criteria by taking advantage of some of the material's properties. When welded, the weld itself and the surrounding material become weaker than the parent (unheated) material creating lines of weakness. By welding the posts of the system onto a baseplate with a gusset detail, the post base becomes weak in comparison to the rest of the post and through careful design, the post will fracture at the base when impacted. This fracture is intentional and in doing so it must remain attached to the rails so that it maintains the spacing of the rails throughout the impact. Once fracture has occurred, the impacting vehicle is redirected through bending and tension in the rail components.

A detailed model of the post is shown in Figure 3. When the post is considered in isolation, the loading that it receives during an impact is almost entirely normal to the line of the barrier because the car only contacts the rail, and the rail transmits the impact forces to the post. The test condition for the post component model is therefore an impact from the generic vehicle model in a direction normal to the post but with the speed component resolved into that direction. The post model predicts a fracture initiating at the top of the gusset and propagating around the weld line until it is completely separated.

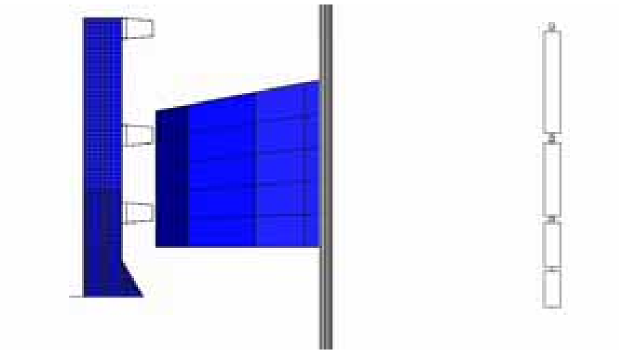

Figure 3: Detailed post model and beam equivalent

The beam model equivalent is shown against the post in Figure 3. The two models are compared on the basis of the reaction force at the base of the post, which is considered to be the most representative parameter as it describes all aspects of the post's behaviour.

The rail is modelled in the same way and a beam element equivalent developed. The test condition for the rail was a length of one 'bay' (the distance between posts), with each end constrained in translation but free in rotation. The model is impacted by the generic vehicle (a car) at full speed and at the true impact angle. Due to the restraints employed, the rail eventually collapses in section and this is considered failure of the rail. The shell and beam element representations of the rail are shown in Figures 4 & 5. Again, the beam and detailed models are compared on the basis of reaction forces at the end of the rail, and also on deflection.

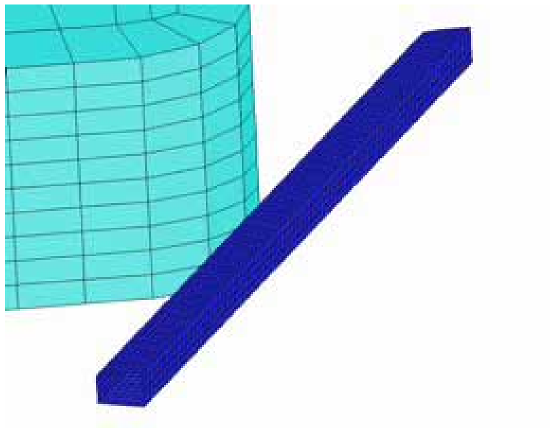

Figure 4: Detailed model of the rail

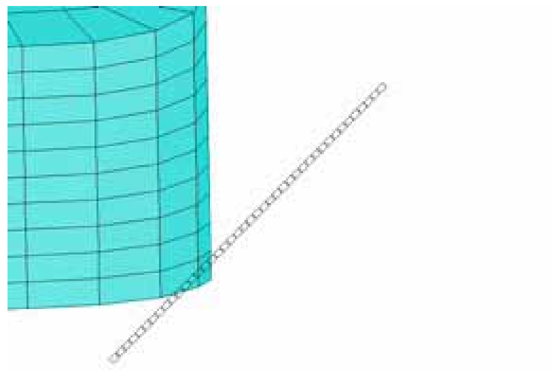

Figure 5: Beam element model of the rail

As the rail transmits the impact loads into the posts, it must be ensured that the rail has sufficient strength to transfer those loads. In particular, the rail must be able to transfer sufficient load into the post to cause post fracture. If the rail does not have this strength, the rail will fail before the post and the vehicle will 'punch through' the restraint system. To check the rail strength, the reaction forces at the rail ends at two times are monitored. The first point is when rail section collapse occurs, and the second is when the plastic strain in the rail reaches the failure strain. If the lower reaction force of these two key stages is lower than the failure load of the post, then the rail has insufficient strength.

Once these component models have been developed as both detailed and simplified representations, the simplified versions are assembled in a full system model and impacted by the vehicle (Figure 6). This complete system model will be representative of the full scale test.

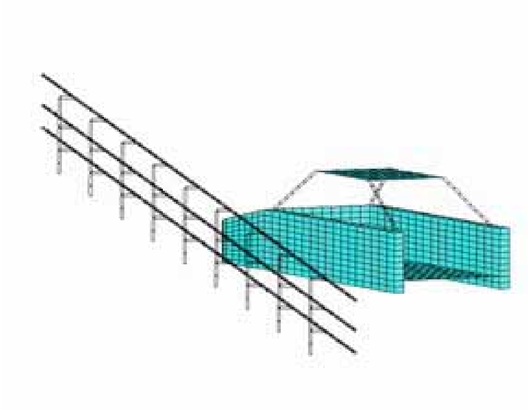

Figure 6: Complete System Model

A full scale test was performed for the aluminium parapet in question and the outcome was found to correlate very well with the predicted results. Injury severity measures such as Acceleration Severity Index (ASI), Theoretical Head Impact Velocity (THIV) and Post impact Head Deceleration (PHD) were all within 5-10% of the predicted values. The dynamic deflection of the system was over-estimated by the model, but this was expected because the most pessimistic (conservative) values for material properties were used throughout. Another key indicator is the number of post fractures, and this was accurately predicted by the model.

Reinforced concrete bridge parapet

The intended purpose of this type of parapet is the same as described in Section 5.2, however the manner of operation is quite different. Reinforced concrete parapets are again intended to fracture, but the reinforcement maintains the integrity of the structure and allows deflection through elastic and plastic deformation. In this case only one panel of the parapet was modelled because unlike metal systems, adjacent bays are unattached and operate independently.

Because only one panel was required in the model, the parapet could be modelled to a reasonable level of detail, but the generic vehicle model was used for the impact. The concrete was modelled using solid elements and the reinforcement was embedded into the model using beam elements. The full scale test item included strain gauges on the reinforcement and so the stress in the beam elements was monitored for comparison against the strain gauge results. The model is shown in Figure 7.

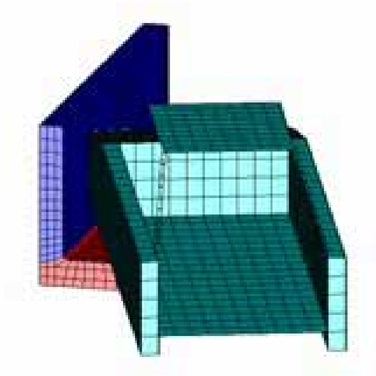

Figure 7: Reinforced concrete parapet impact model

The results of the full scale test correlated well against the predicted values, including vehicle accelerations, parapet deflection and also stresses in the reinforcement. The defection was again slightly over-predicted for the same reasons as described in Section 5.2

Wire-rope safety fence

A safety fence is a considerably less stiff system than a parapet. The intention of the safety fence is to redirect the car safely with minimum likelihood of injury to the car occupants, given the available ‘working width’ for the system. Safety fences are usually seen on the verge and in the central reserve of highways. The available working width for these systems is the amount of deflection that is available so that the impacting vehicle will neither contact a fixed obstacle nor will it interfere with oncoming traffic on the opposite carriageway. This available working width is therefore dependant on, for instance, the width of the central reserve or the amount of space at the side of the carriageway that is free from obstacles.

Typical safety fences systems include ‘W’ beam guard-rails and cable, or wire-rope, systems. The analysis of wire-rope systems presents a number of specific modelling difficulties. The ropes are generally supported by the posts but not fixed to them. For instance, a typical system may consist of ropes located in a slot in the top of the post, or interwoven between the posts. A key feature of these systems is the pre-tensioning of the cables which will influence the deflection and redirect the vehicle during an impact.

The mechanism of cable release from the posts is an important aspect as the extent of ‘free’ (released) cable influences the performance of the system. The cable is generally released in one of two ways: it is either forced to separate as the vehicle runs over the relatively weak post, or the cable is 'flicked' out of its locating slot in advance of the vehicle reaching that post. The latter mechanism is often observed as a vertical wave in the cable.

Wire-rope systems tend to rely on the cables connecting with the vehicle by either catching and locating on a part of the bodywork (for instance the wing mirror) or by forming a groove in the vehicle's bodywork. Again, it is essential to capture this behaviour.

Work has been progressing on the FE modelling of these systems, and to date component models have been developed for location, contact and release of the cable model from a beam element representation of the post (Figure 8). This process has involved the development of techniques for representing interaction between cable elements and beam elements in a highly non-linear and dynamic environment. Running down of weak posts has also been demonstrated, but to date the representation of pre-tensioned inter-woven ropes has proved very difficult to model due to model initialisation and equilibrium instabilities.

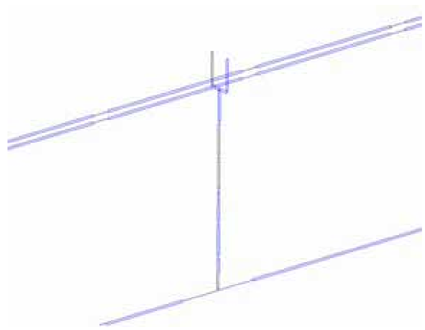

Figure 8: Model of cable interaction with beam representation of post

A demonstrator model has therefore been produced which represents a 2-rope system (not an in-service or tested system) and is shown in Figure 9. All of the relevant effects can be seen including wave effects in the cable resulting in release from the posts and connection between the cables and the vehicle body structure. However, further development is need to represent inter-woven ropes and therefore complete in-service systems.

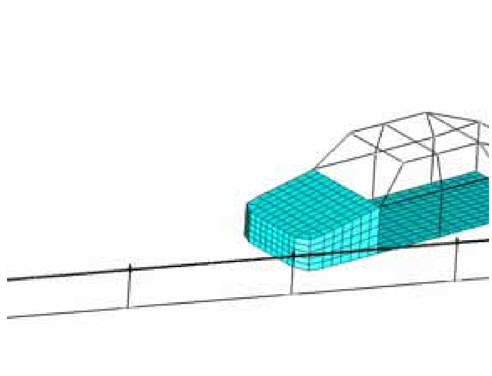

Figure 9: 2-cable wire-rope safety fence model

CONCLUSIONS

Numerical simulation has already been established as an important tool for the study and design of roadside restraint systems. However, the traditional approach of using detailed vehicle models for these analyses has been shown to have difficulties, the most limiting of which is the length of time required to analyse a model.

A novel methodology has been developed by TRL Limited that uses justified simplifications in the representation of the system to reduce the analysis times required and to overcome some of the difficulties of detailed vehicle models. The methodology uses a generic approach to the representation of the vehicle and a beam element representation of the restraint system itself.

The technique has now been used for the analysis of a number of different types of roadside restraint system and has been validated against test data in two ways. Firstly an objective comparison of numerical output has been carried out and secondly a subjective assessment of the capture of key phenomena has been assessed. In both cases the technique has been shown to reliably predict the outcome of vehicle impacts with roadside restraint systems.